2.1 GENERAL

Performance estimates for the stormwater control devices addressed in this report are computed using probabilistic analysis procedures conceived and formulated by DiToro, and developed by DiToro and Small (2,3,4). These procedures provide a direct solution for the long term average removal of stormwater and pollutants for several different modes of operation of a control technique. The variable nature of storm runoff is treated by specifying the rainfall and the runoff it produces in probabilistic terms, established by an appropriate analysis of a long-term precipitation record for an area.

Long-term average reduction in mass loading is considered an appropriate measure of performance for several reasons. It recognizes the highly variable nature of storm runoff, which for a basin of fixed size, will result in higher removal efficiencies during some storm events and lower efficiencies in others. In addition, characterizing basin performance in this manner provides a direct tie-in with the methods adopted by NURP for characterizing the intermittent and variable impacts of storm runoff on water quality and for evaluating significance in terms of protectiveness or impairment of beneficial uses.

For assessing performance, the specification of the size or design capacity of a control device is often ambiguous, because the rate and volume of individual storm runoff events vary so greatly. This is influenced by regional differences in rainfall patterns, by the size of the drainage area the device serves, and by the land use distribution of this area, which determines the degree of impervious cover and the amount of runoff that any particular storm generates. For the procedures used in this report, variable rainfall/runoff rates, volumes, durations, and intensities are specified as a MEAN and COEFFICIENT of VARIATION (CV = STANDARD DEVIATION / MEAN). A meaningful measure of device size or capacity is then the ratio of its volume or flow capacity to the volume or flow rate for the MEAN storm runoff event. This permits a convenient generalization of the analyses performed and allows results to be readily applied to various combinations of local conditions.

Analysis procedures for computing size-performance relationships for three operational modes are presented in this section. A particular stormwater control device may incorporate one or more of these modes. Estimating performance for specific devices (for which examples are presented in later sections of the report) requires selecting and combining the procedures for the modes that are appropriate, or adapting the procedures to the specific circumstances dictated by the nature of the device.

2.2 RAINFALL

A long-term record of hourly precipitation data, available from the U.S. Weather Service for many locations, may be separated into a sequence of discrete storm "events" for each of which volume, duration, average intensity, and interval since the preceding event can be readily determined. The full set of values for each of these parameters may then be statistically analyzed to determine the mean and standard deviation, as well as the probability distribution of the set of all values for a parameter. A NURP publication (1) documents a computer program (SYNOP) that computes these statistics (and other information) from a USWS hourly precipitation record.

Appendix Section 2 provides a tabulated summary of storm statistics for gages in various parts of the country, developed from analysis of rain gage data by the SYNOP program. Appendix Section 3 presents information for estimating runoff coefficient. This information is provided to assist the user in estimating appropriate values for local analyses.

Analysis of a number of rainfall records indicates that the storm parameters that are used in the analyses described in this report are well represented by a gamma distribution. This distribution has accordingly been incorporated in the probabilistic analysis procedures described in this report.

2.3 FLOW - CAPTURE

This procedure addresses the condition where a device captures 100% of all applied flows, up to its capacity QT, and bypasses all flows in excess of this. No consideration is given to what happens to the "captured" fraction, other than that it no longer discharges with the uncontrolled fraction. Some examples include the following: in a Combined Sewer Overflow situation, the amount of the total wet weather flow that is carried away from the overflow point by an interceptor sewer and conveyed to a downstream sewage treatment plant can be considered to have been "captured," or removed from the overflows that would otherwise occur. A recharge device that diverts a portion of the runoff by causing it to percolate into the ground has captured some fraction of the surface runoff that would otherwise completely flow into a surface water body.

Whether or not further consideration must be given to the storm runoff so captured is not addressed here. The technique simply determines the long-term average reduction (or capture) in stormwater volumes processed by the device, and the pollutant loads associated with them.

For storm flows that are gamma distributed, and a device that captures all inflows up to a rate, QT, the long-term fraction not captured is given (3) by :

$$f_{FC} = \frac{r_1^{r_1} e^{-r_1}}{G(r_1)} \int_0^{\infty} E \left[E + \frac{QT}{QR} \right]^{r_1 - 1} \exp\left[-r_1 E\right] dE \quad (1)$$

where:

f_{FC} = fraction not removed by Flow-Capture device

r_1 = $1/CV^2$ (reciprocal of square of CV of runoff flows)

$G(r_1)$ = Gamma function for r_1

E = q/QR - QT/QR

q = runoff flow rate for an event

QR = mean storm runoff flow rate

QT = flow rate capacity of device

Transformed for numerical integration by Laguerre quadrature, this performance equation becomes:

$$f_{FC} = \frac{r_1^{r_1 - 2} e^{-r_1 (QT/QR)}}{G(r_1)} \sum_{j=1}^{n} w_j \, f(x_j) \qquad (2)$$

where:

$f(x_j)$ = $x_j \, (x_j / r_1 + QT/QR)^{r_1 - 1}$

x_j, w_j = abcissas and weights for Laguerre quadrature

This equation has been solved for a range of values for normalized treatment capacity (QT/QR), and variability of storm runoff flows (CV_q). Results are presented in Figure 1 which illustrates the effect of the above variables on long-term control efficiency of a device with this mode of operation.

2.4 FLOW - TREATMENT

This procedure addresses the performance of a device under variable input flows, when the treatment or removal efficiency for a pollutant varies with the rate of applied flow. It differs from

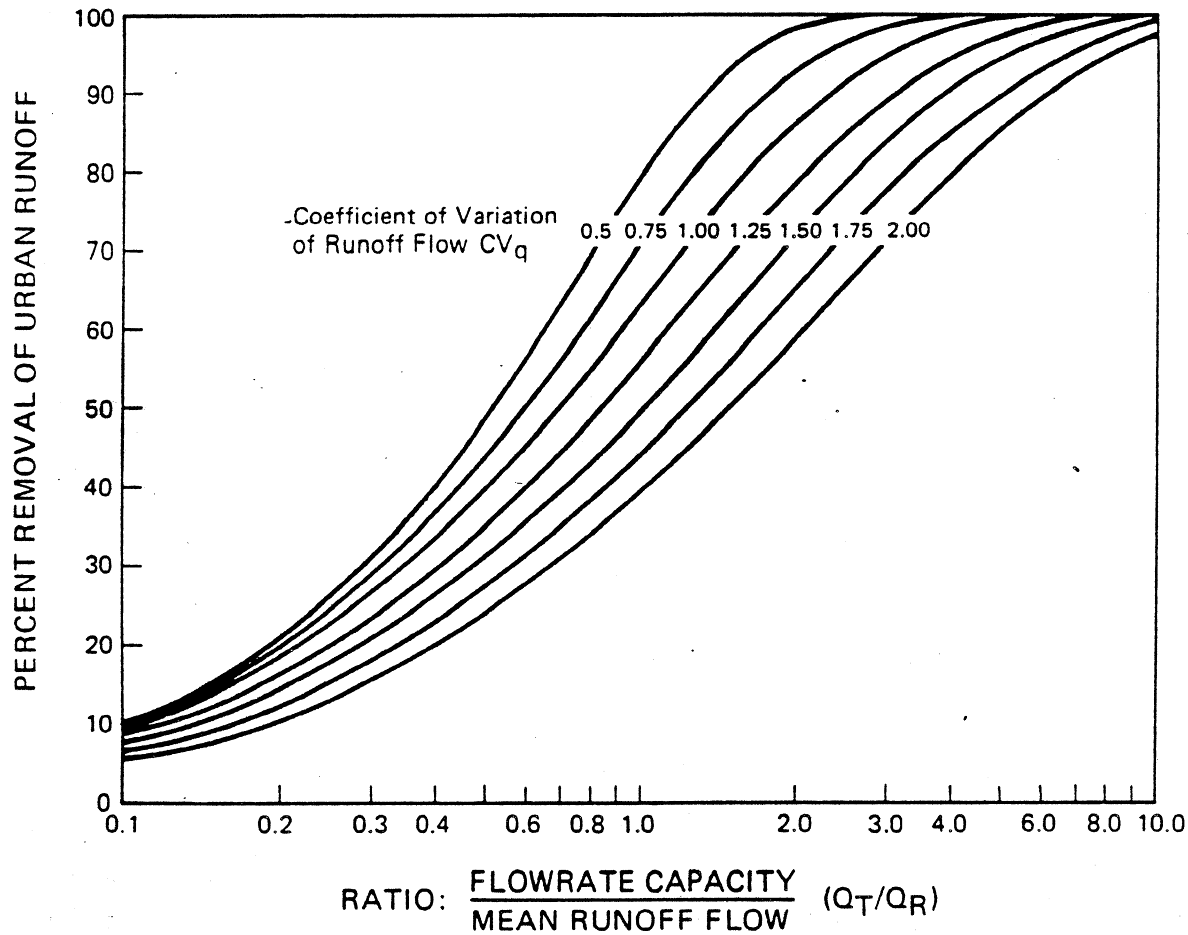

Figure 1. Average long term performance:
flow-capture device

the previous case in that the entire runoff flow is processed. An example would be a sedimentation basin which is less efficient at higher flow-through rates than it is at lower ones.

For variable runoff flows entering a treatment device that are gamma distributed and characterized by a mean flow and coefficient of variation (CV_q), the long-term average fraction of total mass removed is:

$$R_L = Z \left[\frac{r}{r - \ln\left[\frac{R_M}{Z}\right]} \right]^{r+1} \tag{3}$$

where:

R_L = long term average fraction removed

R_M = fraction removed at mean runoff rate

r = $1/CV^2$ (reciprocal of square of CV_q)

CV_q = coefficient of variation of runoff flow rates

Z = maximum fraction removed at very low rates

A graphic solution to this equation is presented by Figure 2 and illustrates the effect on long-term performance caused by variability of stormwater flows. The analysis assumes that removal efficiency of the device is an exponential function of flow, thus:

$$\text{FRACTION REMOVED} = 1 - \exp(Q/k) \tag{4}$$

While not exact, this relationship appears to approximate many removal relationships adequately, and is appropriate for a planning level analysis.

2.5 VOLUME - CAPTURE

This procedure addresses devices whose effectiveness is a function of the storage volume provided. This mode of operation is illustrated by a basin that captures runoff flows until it is filled and thereafter passes (untreated) all additional stormwater. The captured stormwater runoff is then removed from the basin in some manner once runoff ceases, in preparation for the next event.

The analysis does not consider what happens to the captured volume; it simply assumes it to be removed from the total discharge processed by the device. Off-line detention basins for

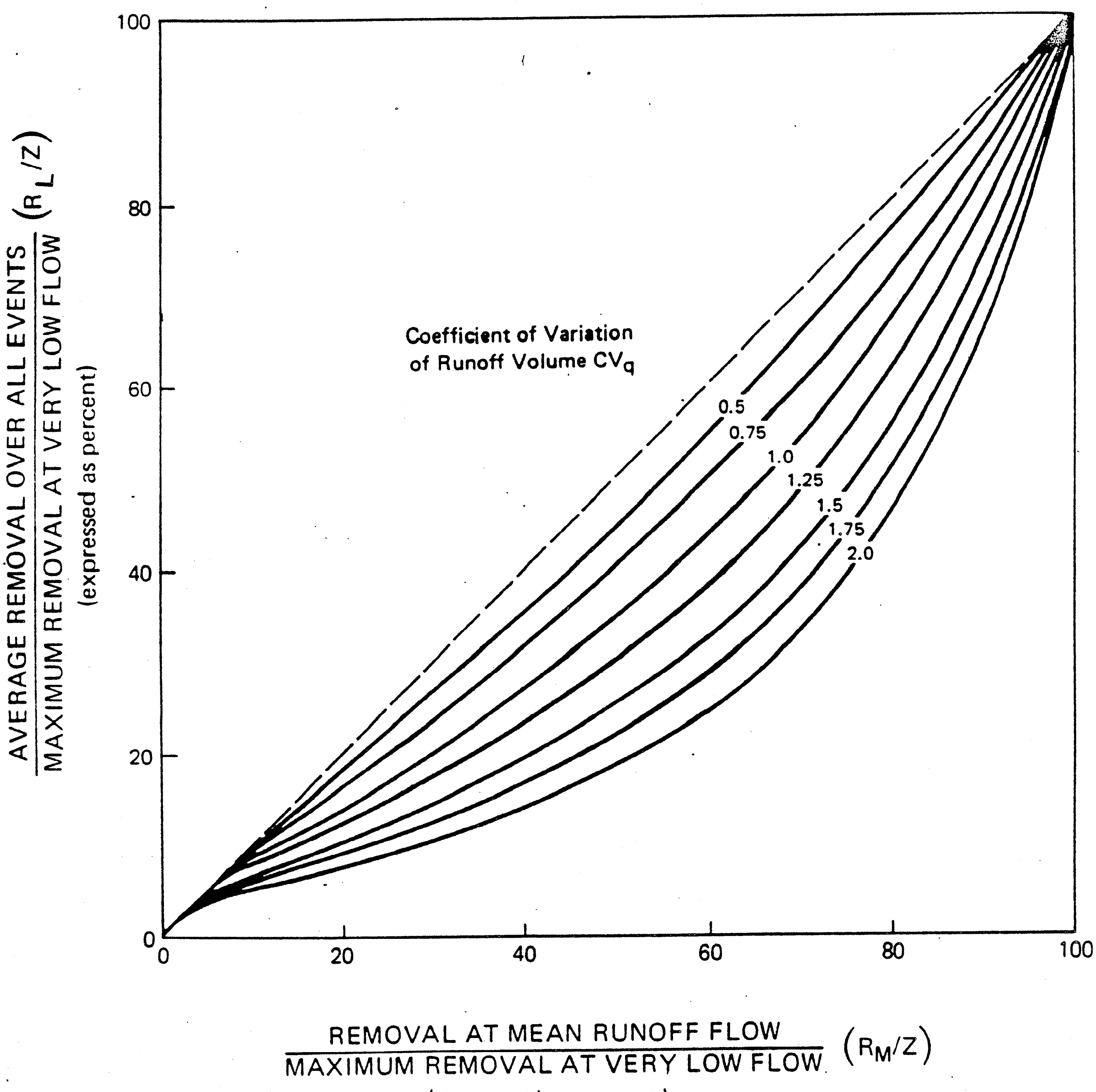

Figure 2. Long term performance of a device where removal mechanism is sensitive to flow rate

CSOs, which pump captured overflows back to the sewer system for processing at the treatment facility, provide one example of this mode of operation. Another example is a recharge basin, which (in addition to operating as a Flow-Capture device, Section 2.3) removes captured runoff volumes through percolation.

For storm volumes that are gamma distributed, the fraction not captured, over all storms, is:

$$f_v = \frac{r_1^{r_1} \; r_2^{r_2}}{G(r_1)\; G(r_2)} \int_{q=0}^{\infty} q^{r_1} \exp\left[\frac{r_2 V}{q}\right] \exp\left[-r_1 q\right] \int_{\Delta=0}^{\infty} \Delta \left[\Delta + \frac{V}{q}\right]^{r_2 - 1} \exp\left[-r_2 \Delta\right] d\Delta \; dq \qquad (5)$$

where:

r_1	=	$1 / CV_q^2$ and $r_2 = 1 / CV_d^2$
CV_q	=	coefficient of variation of runoff flow rates
CV_d	=	coefficient of variation of runoff durations
q	=	storm runoff flow rate
Δ	=	average interval between storm midpoints
V	=	basin effective volume, divided by mean storm runoff volume (VE / VR)
f_V	=	fraction of all volumes <u>NOT</u> captured by basin

The double integral cannot be evaluated analytically. A numerical technique using a Laguerre quadrature to approximate the integral with a weighted polynomial is applied. The basic equation transformed for solution using quadratures is:

$$f_v = \frac{r_1^{r_1} \; r_2^{r_2}}{G(r_1)\; G(r_2)} \sum_{k=1}^{n} w_k \, g[x_k] \left[\sum_{j=1}^{n} w_j \, f[x_j, x_k] \right] \qquad (6)$$

where:

$$g(x_k) = \left[\frac{x_k}{r_1}\right]^{r_1} \left[\frac{1}{r_1}\right] \cdot \exp\left[-r_1\, r_2\, V/X_k\right]$$

$$f(x_j, x_k) = \left[\frac{x_j}{r_2}\right]\left[\frac{1}{r_2}\right]\left[\frac{x_j}{r_2} + \frac{r_1 V}{x_k}\right]^{r_2 - 1}$$

n = number of orders used in integration

X_j, X_k, W_j, W_k = abcissas and weights for Laguerre Integration (from any handbook of mathematical functions)

This integral has been solved for a range of values of V (=VE/VR) and values for coefficient of variation in a range typically observed for rainfall/runoff. Results are plotted in Figure 3, which may be used instead of the equation.

From this figure, the average long-term performance of a volume device may be estimated based on the basin volume relative to the mean storm volume and the variability of individual event volumes being processed. However, the relationship is based on "effective" basin volume (VE) which may be quite different than the physical storage volume of the basin (VB). In the original CSO application, DiToro and Small (3,4) present a procedure for approximating the effective volume, based on an emptying rate ratio (E):

$$E = \frac{\Delta\, \Omega}{VR} \tag{7}$$

where:

Δ = average interval between storms (hours)

Ω = rate at which basin empties (cu ft / hour)

$\Delta\Omega$ = volume removed between storms, on average (cu ft)

VR = runoff volume from mean storm (cu ft)

The effect of the emptying rate ratio on the fraction of physical basin volume which is effective is described by Figure 4. As indicated, in cases where the volume which can be removed in the average interval between storms is small relative to the storm volume which enters on average, much of the available volume may be occupied with carryover from prior storms each time it rains. In such cases, effective volume may be considerably smaller than the physical storage volume provided.

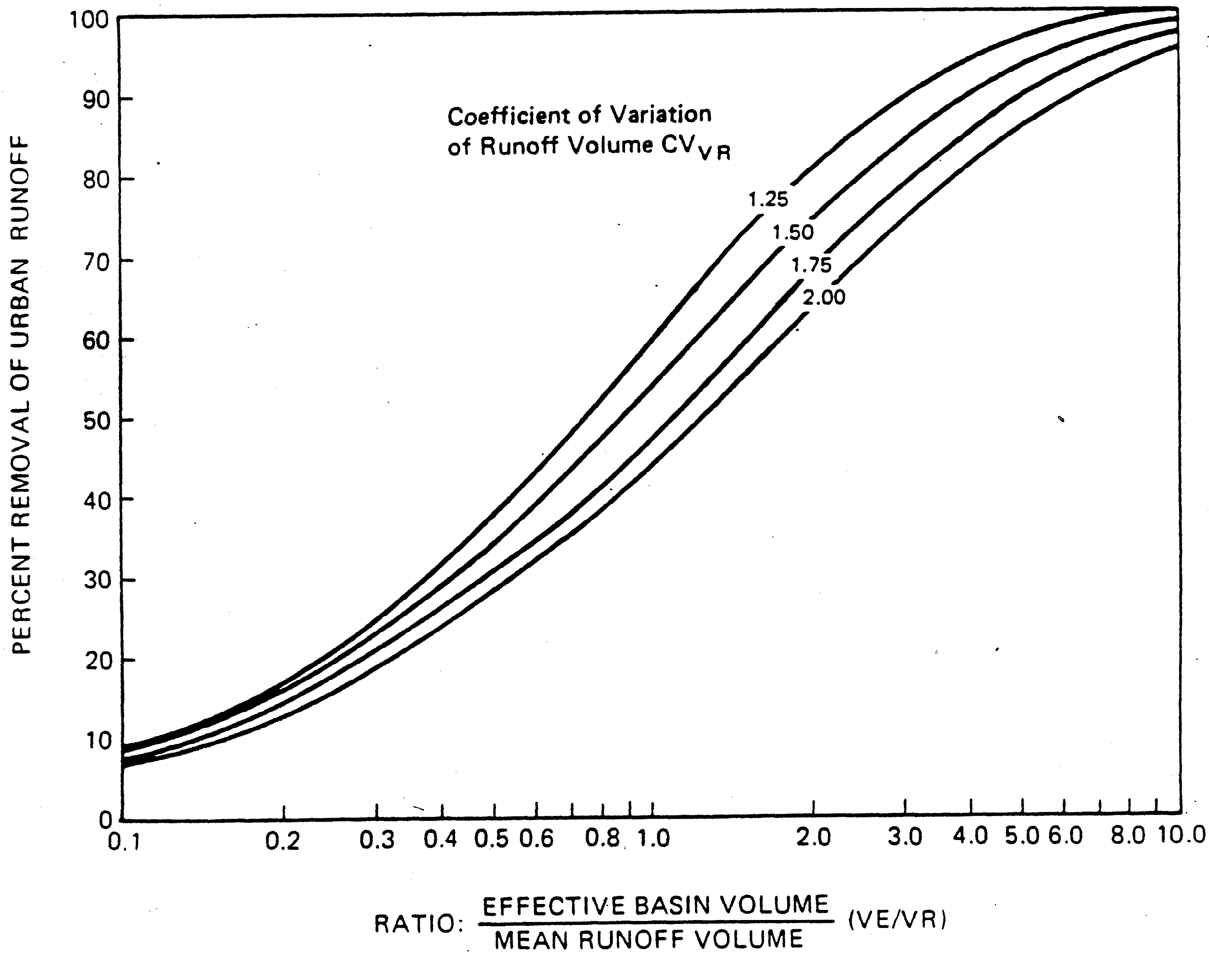

Figure 3. Average long term performance: volume device

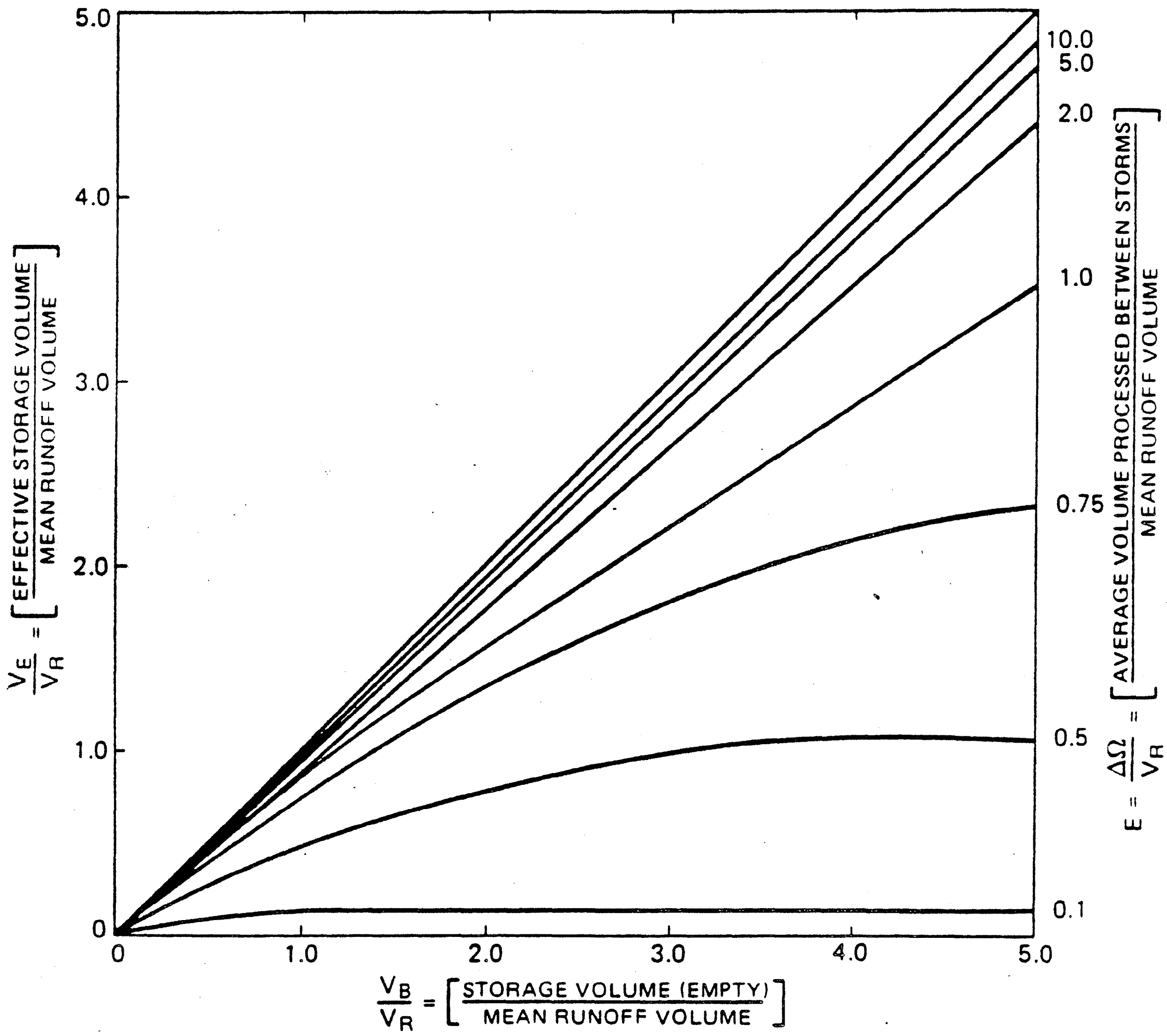

Figure 4. Effect of Previous Storms on Long-Term Effective Storage Capacity

The expression $\Delta\Omega$ may be thought of as the volume emptied from the basin during the average interval between storm events. The smaller this quantity is relative to VR, the average volume entering the basin during storms, the more likely it is that the basin will still contain leftover runoff when a storm begins, and the smaller will be the effective volume. When this ratio, E, is less than about 2, the effective volume becomes quite small compared with the physical volume provided, especially for the larger basins.